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SPLASH TRANSPORT OF ORGANIC CARBON AND ASSOCIATED CONCENTRATION AND MASS ENRICHMENT RATIOS FOR AN OXISOL, HAWAI'I

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ABSTRACT

Rainsplash is an important component of interrill erosion. To date, few studies have critically examined the linkages between aggregate entrainment by splash and associated nutrient flux. An Oxisol was used in laboratory rainfall experiments with two different antecedent moisture contents (AMC) and ten different rainfall energy flux densities (EFD). Splash and soil organic carbon (SOC) flux increased with increased EFD regardless of initial AMC. Aggregates were not transported in proportion to their content in the original soil matrix, those of 2000–4000 μm and < 105 μm were found to be the most resistant to splash. Energy required to detach 1 gC varied from a median of 1870 J for the 2000–4000 μm fraction to 120 J for the 425–850 μm fraction. Temporal variation in cumulative splash flux and carbon flux for various combinations of AMC and EFD indicated distinct patterns. Under dry AMC, splash increased during 1 h duration storms and this was explained by increased aggregate breakdown by air-slaking, decreased soil strength and increased erodibility as soil moisture increased. Wet soil runs exhibited the opposite pattern of decreased flux with time, probably indicating a complex response to limited aggregate availability, increased seal development by raindrop compaction, and transient water layer effects in drop impact craters. The formulation of mass-based SOC enrichment ratios (ER) clearly indicated preferential detachment and transport of splashed aggregates between 250 and 2000 μm. A reliance of chemical transport models on concentration-based ER values can be misleading, because it is the balance between nutrient concentration and sediment quantity that is important for soil quality and non-point source modelling.

KEY WORDS rainsplash; soil organic carbon; enrichment ratios; aggregate fractions; oxisol

INTRODUCTION

Over the last decade there has been a significant increase in research on soil organic matter (SOM), particularly on the C fraction (SOC) since it is an integral component of the global C cycle. The total C content of Earth's soil organic pool exceeds the combined C pool in the atmosphere plus that in the biomass (Eswaran *et al.*, 1993). Major changes in the terrestrial C pool may have significant effects on the global climate system. Besides being a critical component of the global C cycle, SOM influences the physical and chemical properties of soil far out of proportion to the minor concentrations present, and is thus one of the most important components of soils. Briefly, the functions of SOM include the following:

1. Soil organic matter has a biological function in that it provides C as an energy source to N-fixing bacteria, enhances plant growth, root initiation, yield, nutrient uptake, chlorophyll synthesis and seed germination (Schnitzer, 1991).
2. Its physical functions include maintenance of water-stable soil structure because organo-mineral associations bind soil particles and aggregates together (Tisdall and Oades, 1982; Ross, 1993), thereby enhancing water percolation, water retention and aeration (Volk and Loeppert, 1982; Schnitzer, 1991).

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3. The chemical functions of SOM are manifest by its ability to interact with metals, metal oxides and hydroxides, and clay minerals to form metal–organic complexes and act as ion exchangers (cation and anion) and also as a storehouse of N, P and S (Schnitzer, 1991).

To date, most of the soil erosion research dealing with SOM has focused on its relationship to aggregate stability, its use as an index of soil erodibility, its concentration influence on erosion, and its enrichment associated with erosion processes. The seminal work of Tisdall and Oades (1982) verified the strong correlation between SOM and aggregate stability for temperate soils. This relationship has also been observed by numerous researchers for non-peat applied organic matter (e.g., Chaney and Swift 1984; Ekwue 1990, 1991). The general consensus of this body of work is that as SOM increases, aggregation also increases, and thus erodibility should decrease because soil resistance to detachment and transport is increased. This suggests that a strong negative correlation should exist between soil erosion and SOM. However, El-Swaify and Dangler (1976) found SOM concentration to be one of the 20 variables least correlated with the erodibility factor (K) in the USLE for 12 Hawaiian tropical soils ($r^2 = 0{\cdot}014$). In contrast, aggregate stability factors were the most highly correlated factors with K values ($r^2 = 0{\cdot}59$ to $0{\cdot}82$).

Results from the literature relating splash detachment to SOM or SOC have been mixed when the whole soil is considered in a 'lumped' fashion, rather than focusing on aggregate size fractions. Splash and SOC whole-soil studies are difficult to interpret because not all aggregates are detached and entrained in the same proportion to that existing in the *in situ* soil, and different aggregate size fractions may have variable concentrations of SOC. Verhaegen (1984) found no significant relationship between splash and SOC (1·11–4·87 per cent) for 20 loamy Belgian soils ($r = -0{\cdot}26$, $P > 0{\cdot}05$); Bryan (1974) found only a weak statistically significant correlation ($r = -0{\cdot}24$, $P < 0{\cdot}05$) between SOM (0·76–4·13 per cent) and splash for 26 soil types from western Canada ranging in texture from clay to loamy sand. Luk (1979) generally noted significant correlations when all data for four soils from western Canada were grouped (textures ranged from loam to sandy loam, with mean SOC contents ranging from 2·1 to 8·9 per cent). However, on an individual soil basis no significant correlations were established with SOC and splash. The work of Ekwue (1990, 1991) indicated significant decreases in splash detachment with increasing SOM from sandy Entisols from the Rothamsted Experimental Station, England, especially under grass ley treatments. The correlation between splash detachment from grass treated plots and SOM was $-0{\cdot}979$ ($P < 0{\cdot}05$) with a range in SOM of 1·23–5·64 per cent. Ekwue *et al.* (1993) found significant decreases in splash as levels of OM incorporation were increased in an Entisol and Vertisol from Nigeria. The previous results must be compared to those of Yamamoto and Anderson (1973) who examined splash detachment from 32 soils obtained from forested locations on Oahu, Hawai'i, mostly Entisols and Oxisols with a mean SOC of 5·93 ± 2·23 per cent (± one standard deviation). They observed increased total splash and peak splash with increasing SOC, though detailed data and correlation coefficients were not presented. However, they noted that a change in SOC from 3 to 10 per cent, for soils with a similar mean soil erodibility index, resulted in a 73 per cent increase in peak splash from 1·1 to 1·9 $\mathrm{g\,min^{-1}}$. These studies are noteworthy in that they have not examined: (1) relationships between SOM and splash mass on an aggregate size basis; (2) the SOC content of individual aggregate fractions; nor (3) the environmental controls on splash and thus C flux.

The objectives of this study were to quantify variations in splash mass flux, splash SOC concentration and splash SOC flux on an individual aggregate size basis and to examine their relationship with rainfall energy flux densities (EFD) and antecedent moisture contents (AMC). These data will be used to determine whether splash detachment and entrainment is a selective or aselective process at the aggregate level. Additionally, the variation of SOC concentration with aggregate size and its subsequent transport will be used to assess the nutrient enrichment ratio (ER) from two perspectives: (i) concentration, and (ii) mass. It is argued here that nutrient enrichment ratios, included in chemical transport models, should be based on mass–aggregate size relationships rather than on concentration. It is incorrect to infer that a high nutrient enrichment ratio, based on chemical concentration for a given size fraction, is deleterious to on-site or off-site quality issues. The high ER value may be balanced by a negligible flux of sediment, therefore overall it may be insignificant.

MATERIALS AND METHODS

Soil selection, preparation and characteristics

The Wahiawa Oxisol was collected at the Poamoho Experimental Station, central Oahu, Hawai'i. This soil was selected for detailed study because it is a typical, well-weathered tropical soil; it is an important agricultural soil in Hawai'i; erosion of this soil has been linked to non-point source pollution, and its physical and chemical characteristics are well documented. Additionally, an Oxisol was selected since this soil order covers the greatest percentage of land area in the tropics, i.e. 23 per cent (Sanchez and Logan, 1992), and it accounts for 23·5 per cent of the SOC stored in tropical soils (119 Pg) or about 8 per cent of the global SOC store (Eswaran *et al.*, 1993).

The Wahiawa soil is an acidic (pH_{H_2O} = 5·9), kaolinite-rich Rhodic Eutrostox, with the following oxide concentrations: SiO_2 = 38·1 per cent, Al_2O_3 = 35·4 per cent and Fe_2O_3 = 18·2 per cent. The average dispersed particle size (sonification plus calgon) is 80 per cent $<2\,\mu m$, 10·0 per cent 2–20 μm, 2·0 per cent 21–31 μm, 4·0 per cent 31–63 μm, and 4·0 per cent $>63\,\mu m$. It is generally considered to be well aggregated and well drained (El-Swaify, 1980). The soil used in this study was collected from a midslope location (7 per cent slope) to a depth of 15 cm. Samples were air-dried, and sieved through a 4 mm square-hole sieve. The experimental soil has developed from basaltic rock, and covers an area of approximately 52 000 ha on Oahu (Foote *et al.*, 1972). Median annual rainfall in the area is about 1150 mm. In this study a low EFD rainfall event is arbitrarily defined as a 1 h storm event with an EFD $<$ 0·16 W m^{-2}, which is equivalent to a natural rainfall intensity of $\approx$25 mm h^{-1} (or a simulator rainfall intensity of $\approx$50 mm h^{-1}) and has a return period of approximately 1·0–1·5 years.

Rainfall simulation

A laboratory drip-type simulator based on the design of Munn and Huntington (1976) and described in detail by Garnier (1988) was used for detailed rainsplash investigations. Raindrop fall height was 1·35 m, and uniform drops with a median diameter of 3·2 mm were produced. Domestic water supply was used for all tests. Ten experiments were conducted using rainfall intensities ranging from 17 to 118 mm h^{-1}, which correspond to EFD values of 0·052 and 0·36 W m^{-2} respectively. This simulator produced drops with 51 per cent of the EFD associated with natural rainfall at the same intensity. Five runs had low EFD values and five had high EFD values. To approximate a random distribution of raindrops at the soil surface, two opposing fans were used to generate the necessary turbulence.

Data collection

During each of the ten experiments eight specially designed 7·7 cm (i.d.) segmented splash depletion cylinders were subjected to rainfall. Each cylinder was two-tiered, with the upper 1 cm section detachable from the lower 5 cm segment. Sieved air-dried soil was packed into each cylinder (6 cm in height) to a bulk density of approximately 1·00 Mg m^{-3} which is within the range of field bulk densities (0·92–1·09 Mg m^{-3}). Each splash cylinder was placed at a near-level slope angle within an 8 l collecting bucket to entrap all splash-detached sediment evacuated from the cylinder.

Each experiment at a given EFD was divided into two runs each lasting 1 h. The two sequential runs were conducted initially at an AMC $\leq$ 10 per cent (dry run), and this was followed by a wet run at an AMC between 40 and 50 per cent. After the dry run the upper 1 cm of splash cylinder was carefully sectioned along a pre-cut (sealed) interface. This provided a 'fresh' near-saturated surface layer that was not compacted or depleted in aggregates. During each experiment the 8 l collecting buckets were exchanged at 15 min intervals throughout dry and wet runs.

Aggregate size analysis and enrichment ratio determinations

Following initial sieving of soil through a 4 mm screen, ten samples were dry-sieved for 10 min using a standard Ro-tap shaker. Ten samples were also wet-sieved using a procedure similar to that discussed by Gabriels and Moldenhauer (1978). The following six aggregate sizes were fractionated: 2000–4000 μm (granule-size aggregates); 850–2000 μm (coarse to very coarse-sand sized aggregates); 425–850 μm (medium

Table I. Relative percentage of dry- and wet-sieved aggregate size fractions in the Wahiawa Oxisol

Aggregate size fraction (μm)	Dry-sieved mean (%)	Wet-sieved mean (%)
2000–4000	12·31 (23·0)*	2·35 (15·4)
850–2000	19·37 (9·5)	9·50 (11·3)
425–850	21·26 (2·9)	19·26 (6·9)
250–425	15·32 (6·8)	21·28 (6·2)
105–250	20·50 (10·7)	33·83 (4·1)
< 105	11·24 (10·3)	13·78 (13·9)

* Values in parentheses are coefficients of variation, based on $n = 10$

to coarse sand-sized aggregates); 250–425 μm (medium sand-sized aggregates); 105–250 μm (very fine to fine sand-sized aggregates); < 105 μm (very fine sand-sized aggregates plus silt and clay-sized aggregates). The relative percentage of each dry- and wet-sieved aggregate size fraction is shown in Table I.

Immediately after a simulated rainfall experiment splash time-increment samples were wet-sieved and aggregate size fractions similar to those for the original soil were determined. Total aggregate mass for each 15 min interval was determined by summing the individual aggregate size fractions. Material was placed in small pre-weighed aluminium tins, decanted and oven-dried for 24 h at 105°C. Mass of each aggregate fraction was determined to a precision of ±0·001 g. Splash flux values (kg m^{-2} h^{-1}) were corrected for splash cup area using the equation developed by Poesen and Torri (1988, p. 120) for bare Belgian soils, i.e. splash values were multiplied by a factor of ≈1·52. After drying and weighing, splash for each aggregate size fraction, for a given 15 min time increment, was composited for the eight splash cups. Composited samples were finely ground using a Spectrex 8100 mixer-mill with tungsten carbide bowl and balls for 5 min. This procedure provided a homogeneous sample for C determinations. Generally, 0·3–0·5 g samples were used for total C (per cent) analysis using a Leco WR-12 combustion furnace at ≈1200°C. Standards (0·88 per cent C) were run every tenth sample and readings were corrected to account for minor instrument drift. Ten replicates for selected samples from each aggregate size fraction indicated very low coefficients of variation, generally < 1·8 per cent, and thus high accuracy and precision were obtained. The Leco measures total C (inorganic plus organic); however, inorganic C was negligible in our samples since the soil had a low pH (< 6·0), had not received lime amendments, and negligible C was determined on selected samples following pre-ignition at 450°C for 24 h in a muffle furnace. Therefore, C referred to in this study is considered to be soil organic carbon (SOC). A total of 424 splash samples were analysed for C (excluding replicates). Additionally, ten samples of each individual wet-sieved size fraction (< 4000 μm) were analysed for C ($n = 60$).

Two enrichment ratios were calculated for SOC; the first is based only on the concentration of SOC in splash-transported sediment to that in the soil matrix for a given aggregate size fraction, and is given by:

$$\mathrm{ER_{[SOC]}} = \frac{\mathrm{SP_{[C]}}}{\mathrm{Soil_{[C]}}} \tag{1}$$

where $\mathrm{ER_{[SOC]}}$ is the carbon concentration enrichment ratio; $\mathrm{SP_{[C]}}$ is the carbon concentration in splashed material per aggregate size fraction (gC kg soil^{-1}); and $\mathrm{Soil_{[C]}}$ is the carbon concentration in the original soil matrix per aggregate size fraction (gC kg soil^{-1}).

The $\mathrm{ER_{[SOC]}}$ values provide useful information on the enrichment (ER > 1·0) or depletion (ER < 1·0) of individual size fractions. However, they provide no information on the ER values associated with splash (mass) for individual aggregate size fractions. Thus, misleading interpretations may result. For example, if the $\mathrm{ER_{[SOC]}}$ value for the fine fraction is 3·0 (enrichment), but the actual mass of material transported in this fraction is negligible, its importance in soil C depletion will be limited. This problem can be rectified

Table II. Summary of organic carbon per aggregate fraction of the original soil and individual contributions of aggregate fractions to soil carbon storage

Aggregate size (μm)	Mean soil C (%)*	Soil C 2·5[th] percentile (%)†	Soil C 97·5[th] percentile (%)†	C mass (gC kg soil^{-1})‡	C contribution (%)§
2000–4000	1·818[ab¶]	1·676	1·967	0·428	2·361
850–2000	1·902[a]	1·832	1·975	1·807	9·976
425–850	1·722[b]	1·668	1·781	3·318	18·324
250–425	1·693[b]	1·655	1·735	3·604	19·901
105–250	1·829[a]	1·775	1·875	6·186	34·164
< 105	2·007[a]	1·941	2·070	2·766	15·274

*Tabulated values are based on a wet-sieved sample size of ten that was resampled 1000 times with replacement (cf., Efron and Tibshirani, 1993)

†Percentiles of the sampling distribution

‡C mass = ($\bar{X}$ soil mass per aggregate fraction (g kg soil^{-1})) $\left(\dfrac{\bar{X}\text{ soil C\% per aggregate fraction}}{100}\right)$

§Fractional aggregate contribution = $\left[\dfrac{\text{C mass per aggregate}}{\text{Total C mass}}\right] \times 100$

¶Mean values followed by the same lower case letter are **not** significantly different at α = 0·05

by computing an enrichment ratio based on C mass flux (ER_{CMF}), and is given by:

$$ER_{CMF} = \left[\frac{\left[\dfrac{SP_{CM}}{TSP_{CM}}\right]}{\left[\dfrac{Soil_{CM}}{TSoil_{CM}}\right]}\right] \tag{2}$$

where SP_{CM} is the mass of carbon per aggregate size fraction per time period transported by splash (gC kg soil^{-1} time^{-1}); TSP_{CM} is the total mass of carbon (summation of all aggregate size fractions) splashed per time period (gC kg soil^{-1} time^{-1}); $Soil_{CM}$ is the mass of carbon per wet-sieved aggregate size fraction in the original soil matrix (gC kg soil^{-1}); and $TSoil_{CM}$ is the total mass of carbon in the soil matrix (gC kg soil^{-1}).

Thus, if splashed aggregates of 2000–4000 μm were transported with an ER_{CMF} of 1·0 (no enrichment or depletion) the ratio of $SP_{CM\ 2000\text{–}4000}/TSP_{CM}$ would be approximately 0·0236 or 2·36 per cent, which is equivalent to that in the original soil matrix (i.e. $Soil_{CM\ 2000\text{–}4000}/TSoil_{CM}$; Table II).

RESULTS AND DISCUSSION

Comparisons of dry- and wet-sieved aggregate size distributions for the original soil indicate significant differences (Table I). Following dry-sieving approximately 32 per cent of the aggregates were coarser than 850 μm, compared to only 12 per cent following wet-sieving. There were only minor differences between 250–850 μm fractions and those < 105 μm. However, there was a significant increase from 21 to 34 per cent in the 105–250 μm fraction following wet-sieving. These data indicate that rapid submergence of coarse air-dried aggregates in water causes significant breakdown and production of finer aggregates, especially in the range of 105–250 μm. Slaking is commonly suggested as the mechanism that causes dry aggregates to break down when rapidly wet. Yoder (1936) defined the slaking process as the compression of trapped air within the aggregate and this causes a series of miniature explosions which continue until the aggregate is shattered. Emerson (1967) noted that most aggregates slake due to the stresses induced by entrapped air, and he used this as one of the first indices to classify the stability of soil aggregates. The breakdown of unstable dry aggregates produces sub-units which may also be aggregated. Dexter (1988) noted that rapid wetting of surface aggregates can cause them to slake into micro-aggregates of 20–250 μm. This seems to have occurred for the Wahiawa Oxisol, with the breakdown of aggregates > 850 μm, and production of aggregates primarily within the range of 105–250 μm.

Mean concentrations of SOC in the aggregate fractions show some statistically significant differences (Table II), but there was also significant overlap between several classes. The < 105 μm fraction had the highest SOC content with a mean value of 2·01 per cent (20·1 gC kg soil^{-1}), but this was not significantly different ($\alpha = 0{\cdot}05$) from 1·90 per cent for the 850–2000 μm fraction, or 1·82 per cent for the 2000–4000 μm fraction. Fractions between 250 and 850 μm had the lowest average values, 2·9–3·1 gC kg soil^{-1} lower than the < 105 μm fraction. These results are similar to those reported by Waters and Oades (1991) for an acidic ($pH_{H_2O} = 4{\cdot}6$), kaolinite-rich Oxisol from Australia (3 per cent sand, 70 per cent clay), where wet-sieved aggregates between 53 and 2000 μm differed in SOC by 3·0 gC kg soil^{-1}. Mendonça *et al.* (1991) found SOC concentration differed only slightly between aggregates < 250 μm compared to those > 250 μm for acidic ($pH_{H_2O} = 4{\cdot}1$–$4{\cdot}4$), clay-rich (40–58 per cent) Oxisols under natural forest conditions ($\Delta = 1{\cdot}6$ gC kg soil^{-1}), soils under rubber plantations ($\Delta = 3{\cdot}5$ gC kg soil^{-1}), and under degraded grassland ($\Delta = 1{\cdot}6$ gC kg soil^{-1}). These data indicate that limited absolute differences in SOC occur in wet-sieved Oxisol aggregate size fractions. This may result from the proportional incorporation of fines (primary particles), particularly clays (< 2 μm), fine silts (2–5 μm), and medium silts (5–20 μm), that are generally enriched in SOC in the various aggregate size fractions (cf. Anderson *et al.*, 1981; Tiessen and Stewart, 1983; Christensen, 1992; Schulten *et al.*, 1993).

Variation in splash flux with AMC and EFD

Median splash flux increased with increased EFD for runs with initially dry or wet moisture contents (Figure 1). The curve-fitting technique followed that suggested by Meyer (1981, p. 1473) using $\log_{10}$-transformed data. A power function model fitted the data for the runs with a dry AMC, with the following form:

$$SF_{MF} = 12{\cdot}52\,EFD^{1{\cdot}372} \quad (3)$$

$r^2 = 0{\cdot}959$; $RMS_{error} = 1{\cdot}22\,kg\,m^{-2}\,h^{-1}$; 95 per cent confidence bands of the exponent (*b* value) are 1·140 and 1·604; $P < 0{\cdot}05$. In Equation (3) SP_{MF} is the total splash mass flux (kg m^{-2} h^{-1}), and EFD is the rainfall energy flux density (W m^{-2}).

The *b* value in Equation (3) is significantly different from 1·00 at $\alpha = 0{\cdot}05$, and is comparable to the value of 1·46 found by Free (1960) for a silt loam, 1·34–1·77 for silty clay to loamy sands noted by Bubenzer and Jones (1971), and a value of 1·35 for a clay studied by Quansah (1981). Data for the runs with an initially wet

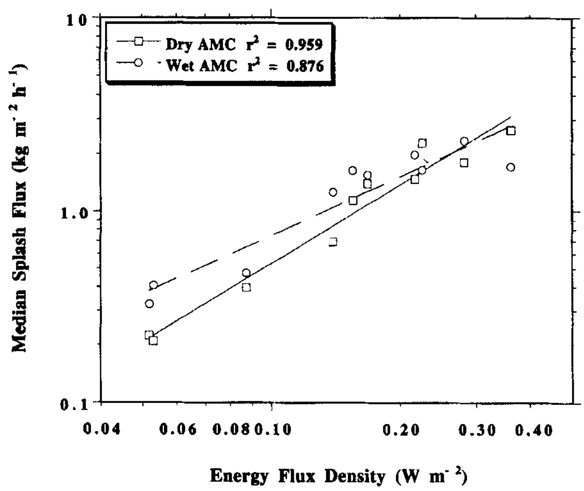

Figure 1. Variation in splash detachment with rainfall energy flux density and antecedent moisture content (AMC). Each data point represents the median for a maximum of 192 values

moisture content were also fitted to a power function model of the form:

$$SP_{MF} = 7{\cdot}89\,EFD^{1{\cdot}024} \qquad (4)$$

$r^2 = 0{\cdot}876$; $RMS_{error} = 1{\cdot}31\,kg\,m^{-2}\,h^{-1}$; 95 per cent confidence bands of the exponent (b value) are 0·710 and 1·338; $P < 0{\cdot}05$.

However, the b value in Equation (4) did not differ significantly from 1·00 or a linear model. This is similar to the results obtained by Watung *et al.* (in press) for the same soil using a fall height of 2·70 m. The exponent in Equation (4) is comparable to those for sandy soils or sediments studied by Free (1960), Quansah (1981) and Poesen (1985). These data indicate that splash flux increased with increased EFD; however, the nature of the relationship varies with AMC and aggregate availability.

Non-parametric paired comparisons of total splash flux between dry and wet AMC runs for similar EFD values and time periods indicated that no significant differences existed. Median splash flux for initially wet runs was $1{\cdot}392\,kg\,m^{-2}\,h^{-1}$ ($n = 40$, 95 per cent confidence bands were $1{\cdot}089$–$1{\cdot}683\,kg\,m^{-2}\,h^{-1}$); this was approximately 17 per cent greater than that for the initially dry runs which was $1{\cdot}162\,kg\,m^{-2}\,h^{-1}$ ($n = 40$, 95 per cent confidence bands were $0{\cdot}633$–$1{\cdot}686\,kg\,m^{-2}\,h^{-1}$). However, due to variability in splash flux, differences between medians were not statistically significant at $\alpha = 0{\cdot}05$.

Variations in SOC concentration with AMC and EFD

Side-by-side boxplot comparisons of SOC concentration for the original soil, to that for all splash samples and for initially dry and wet runs, indicated that significant differences existed (Figure 2). Splashed sediments, regardless of initial AMC, had significantly lower SOC concentrations than the original soil. The median SOC for splashed material from the dry runs was 6·8 per cent less than that from the original soil matrix ($\Delta_{original\ -\ dry} = 1{\cdot}2\,gC\,kg\ soil^{-1}$), and 9·2 per cent less than that for the wet runs ($\Delta_{original\ -\ wet} = 1{\cdot}7\,gC\,kg\ soil^{-1}$). These differences reflect the limited ability of low EFD runs, for all initial moisture contents, to transport aggregates of 2000–4000 μm. This fraction had significantly more SOC than the 250–850 μm fraction. Thus, the failure of splash to detach the coarser aggregates would result in a general decrease in SOC on a whole-soil basis since the proportional contribution of aggregates of 250–850 μm would increase.

Comparison of SOC concentrations between the original soil and the splashed sediment at low and high EFD values indicated a significantly lower percentage during the low EFD runs (Figure 3). This again may be attributed to the absence of aggregates of 2000–4000 μm being transported. Median SOC contents from the low EFD runs were 10·2 per cent less than those from the original soil ($\Delta_{original\ -\ low} = 1{\cdot}9\,gC\,kg\ soil^{-1}$), and 6·5 per cent less for the high EFD runs ($\Delta_{original\ -\ high} = 1{\cdot}2\,gC\,kg\ soil^{-1}$).

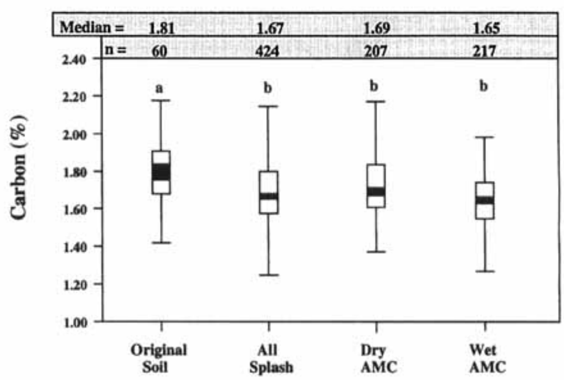

Figure 2. Side-by-side boxplot exhibiting the relationship between carbon concentration in the original soil and that in splashed sediment with different initial antecedent moisture contents (AMC). Outliers were removed for enhanced clarity. Note that individual boxplots with similar lower case letters are not statistically different at $\alpha = 0{\cdot}05$

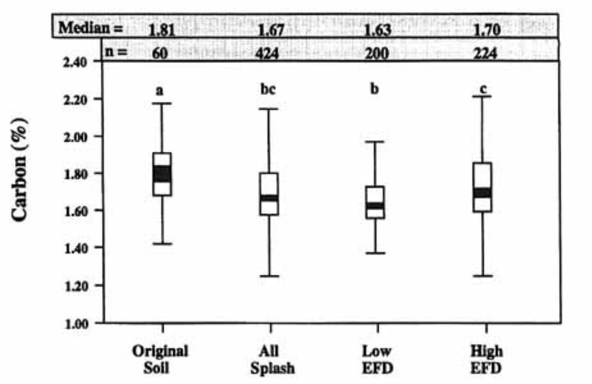

Figure 3. Side-by-side boxplot exhibiting the relationship between carbon concentration in the original soil and that in splashed sediment with different rainfall energy flux densities (EFD). Outliers were removed for enhanced clarity. Note that individual boxplots with similar lower case letters are not statistically different at $\alpha = 0{\cdot}05$

The resistance of individual wet-sieved aggregate fractions to splash detachment varied as did the resistance of SOC to detachment (R_{SOC}), where R_{SOC} is given by:

$$R_{SOC} = \left[\frac{EFD}{SP_{CMF}}\right] e^{0{\cdot}054D} \tag{5}$$

where R_{SOC} is the energy required to detach 1 gC for an individual aggregate size fraction (J gC^{-1}); EFD is the rainfall energy flux density (J m^{-2} s^{-1}); SP_{CMF} is the total carbon splash mass flux (gC m^{-2} s^{-1}); and $e^{0{\cdot}054D}$ is the correction factor of Poesen and Torri (1988), with D equal to the diameter (cm) of the splash cup.

The variation in R_{SOC} for the wet-sieved aggregate size fractions (Figure 4) indicates significant differences

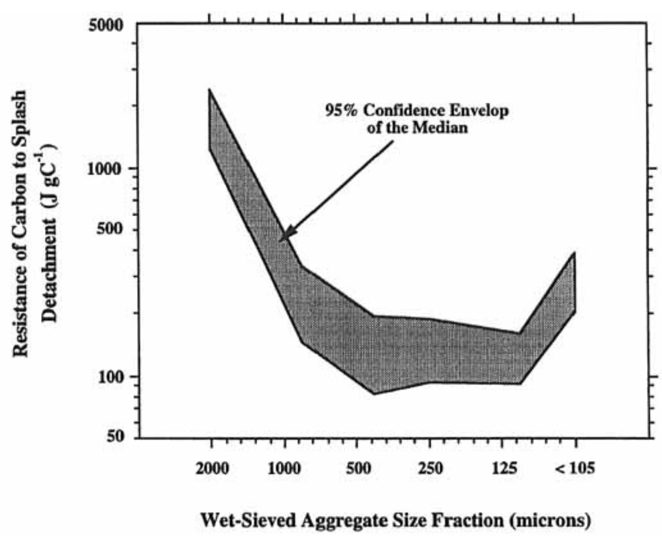

Figure 4. Resistance of carbon detachment to splash for various aggregate size fractions. The upper and lower bounds of the envelope curve were computed from ten energy flux density values per aggregate fraction. Note that 2000 implies a size range of 2000–4000 μm; 850, 850–1000 μm; 425, 425–850 μm; 250, 250–425 μm; 105, 105–250 μm

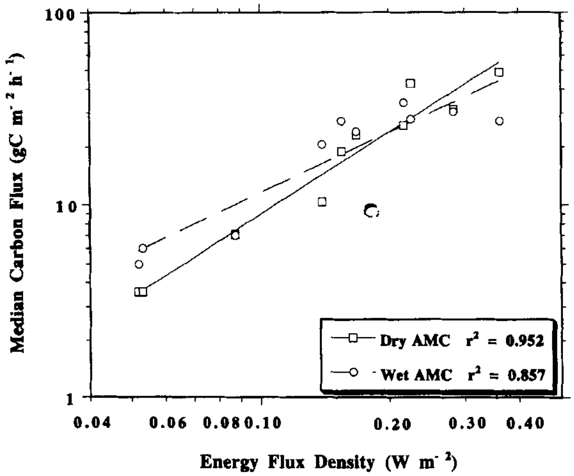

Figure 5. Variation in carbon flux with rainfall energy flux density and antecedent moisture content (AMC). Each data point represents the median for a maximum of 24 values

with the following sequence:

$$R_{2000-4000} > R_{<105} > R_{850-1000} > R_{250-425} \approx R_{105-250} \approx R_{425-850}$$

Thus, the energy required to detach 1 g of SOC from aggregates 2000–4000 μm in diameter ($\approx$1900 J gC^{-1}) is about 16 times that required to detach 1 gC from aggregates 425–850 μm in diameter ($\approx$120 J gC^{-1}). It is also of interest to note that the R_{SOC} value for aggregates < 105 μm is significantly greater (two times) than that for aggregates of 105–425 μm. This increased resistance may reflect increased cohesion, vertical migration to form a filtration layer, or may reflect the shielding of these aggregate sizes at the surface from splash. Comparable data for temperate or tropical soils are not available in the literature.

Variation in SOC flux on a whole-soil basis with AMC and EFD

The carbon flux associated with splashed material (SP_{CMF}; gC m^{-2} h^{-1}) is a function of the concentration of SOC and splash mass flux (SP_{MF}). On a whole-soil basis, as EFD increased SP_{CMF} increased (Figure 5) for all moisture contents. The relationships were similar in form to those previously documented for SP_{MF}, Equations (3) and (4). For the initially dry runs the following power function model best fitted the data:

$$SP_{CMF} = 231{\cdot}2\,\mathrm{EFD}^{1{\cdot}412} \quad (6)$$

with $r^2 = 0{\cdot}952$; $RMS_{error} = 1{\cdot}25$ gC m^{-2} h^{-1}; 95 per cent confidence bands of the exponent (b value) are 1·152 and 1·671; $P < 0{\cdot}05$.

The exponent in Equation (6) was significantly greater than 1·00. The model for the wet runs was:

$$SP_{CMF} = 127{\cdot}1\,\mathrm{EFD}^{1{\cdot}040} \quad (7)$$

with $r^2 = 0{\cdot}857$; $RMS_{error} = 1{\cdot}35$ gC m^{-2} h^{-1}; 95 per cent confidence bands of the exponent (b value) are 0·693 and 1·387; $P < 0{\cdot}05$.

The b value in Equation (7) was not significantly different from 1·00, thus a linear model would be most appropriate to describe the relationship between SP_{CMF} and EFD for wet runs.

Non-parametric paired comparisons aligned by EFD and time increment indicated no significant differences in SP_{CMF} with AMC. The median SP_{CMF} for the dry runs was 20·3 gC m^{-2} h^{-1} ($n = 40$, 95 per cent confidence bands were 10·77–28·49 gC m^{-2} h^{-1}) or 12 per cent less than that for the initially wet AMC runs, 22·8 gC m^{-2} h^{-1} ($n = 40$, 95 per cent confidence bands were 18·52–27·59 gC m^{-2} h^{-1}). These results are similar to those previously discussed for SP_{MF}.

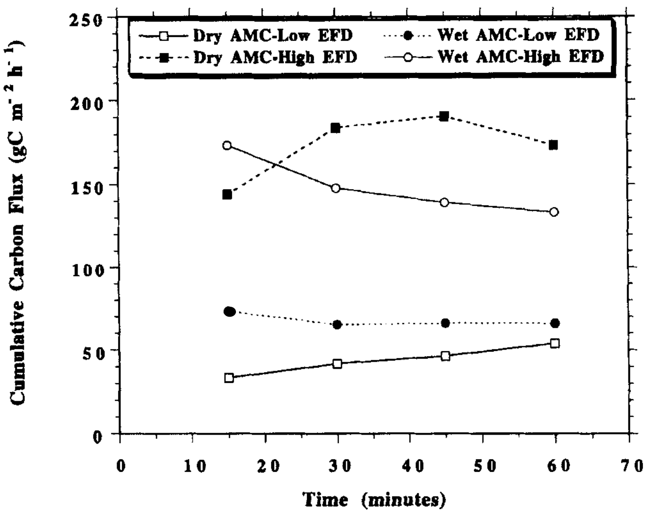

Figure 6. Temporal variation in cumulative carbon flux for various combinations of energy flux density (EFD) and initial antecedent moisture contents (AMC). Each data point represents a summation of five values

Temporal patterns in cumulative SP_{CMF} differed significantly for various combinations of AMC and EFD (Figure 6). These patterns mirrored those for splash (data not shown) in this study, and those discussed by Watung *et al.* (in press). During the wet AMC–high EFD runs, cumulative SP_{CMF} peaked during the 0–15 min time increment and decreased by 23 per cent during the 45–60 min period. This pattern can be explained by a near-saturated soil surface with minimal shear strength, and thus the greatest potential for splash flux existed since availability of aggregates was not limiting. Initial flushing of material and associated C is followed by increased compaction and reduced aggregate and C availability. During the dry AMC–high EFD runs, SP_{CMF} increased by 32 per cent from the 0–15 min time period to the peak during 30–45 min, and this was followed by a 9 per cent decrease during the subsequent measurement period (Figure 6). This pattern suggests an initial period during which aggregate breakdown increases, soil moisture content increases, and movement of aggregates and associated C increase. Decay occurs when material availability decreases or when the surface shields easily transportable aggregates within the developing seal layer. The pattern of cumulative SP_{CMF} during the wet AMC–low EFD runs is similar to that for the wet runs at high EFD, i.e. SP_{CMF} decreased by approximately 10 per cent from 0–15 min to 45–60 min. The temporal pattern of SP_{CMF} during the dry AMC–low EFD runs indicated a 62 per cent increase from the beginning to the end of the experiments. This pattern indicates that energy was the limiting variable. Continued increases in SP_{CMF} are unlikely, as surface sealing and aggregate availability would eventually limit detachment and transport.

A comparison of cumulative SP_{CMF} ratios after 1 h duration storms for each of the AMC and EFD conditions was as follows:

dry AMC–low EFD < wet AMC–low EFD < wet AMC–high EFD < dry AMC–high EFD

1·00: 1·54: 3·39: 3·95

Note the significant increase in C splash flux with increased EFD. Additionally, during high intensity runs the cumulative SP_{CMF} from dry runs was about 14 per cent greater than that from the wet runs. This probably reflects increased aggregate breakdown and thus increased aggregate availability due to slaking of air-dried aggregates at high EFD values.

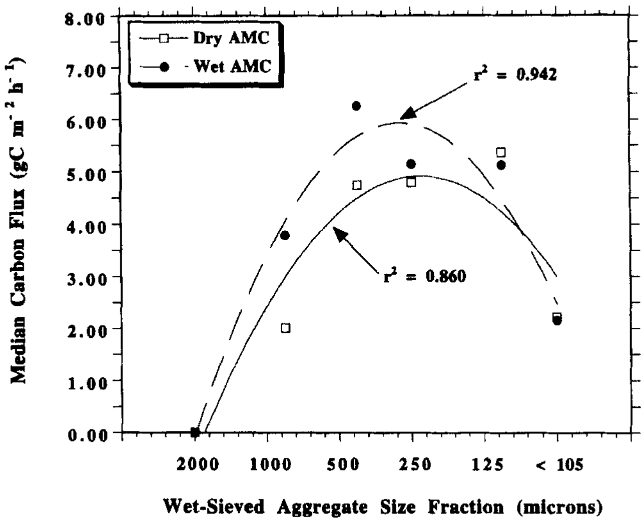

Figure 7. Carbon flux associated with various aggregate size fractions for two different antecedent moisture contents (AMC). Each data point represents a median of 40 values. Note that 2000 implies a size range of 2000–4000 μm; 850, 850–1000 μm; 425, 425–850 μm; 250, 250–425 μm; 105, 105–250 μm

Variation in SOC flux for individual aggregate size fractions with AMC and EFD

Comparisons of median SP_{CMF} values for individual aggregate sizes under dry and wet initial moisture contents (Figure 7) were not statistically significant at $\alpha = 0{\cdot}05$. The exception to this was the 850–2000 μm fraction which had a significantly greater flux under initially wet moisture conditions (3·78 gC m^{-2} h^{-1}) compared to initially dry conditions (2·01 gC $m^{-2} h^{-1}$). This difference cannot be explained by differences in SOC concentration between wet and dry runs for this fraction since the mean difference of 0·25 gC kg soil^{-1} was not significant at $\alpha = 0{\cdot}05$. Thus, differences resulted from variations in SP_{MF}. However, it is not clear why this fraction is preferentially moved during wet runs.

The SP_{CMF} was significantly greater from the high EFD runs for all aggregate size fractions (Figure 8), and this can be explained by significantly greater SP_{MF} under the high intensity events (Figure 1). Additionally, several individual fractions had significantly greater C concentrations during the high EFD runs. This latter point partially explains the difference in C concentration between low and high EFD runs noted earlier on a whole-soil basis (Figure 3). However, it is not clear why fractions other than 2000–4000 μm would have higher C concentrations during high intensity runs. One mechanism that may play a role in explaining these differences is the peeling or stripping of material from an outer layer of structurally stable aggregates under high EFD conditions or when aggregate strength is at a minimum. Ghadiri and Rose (1991) observed the non-uniform distribution of chemicals within soil aggregates, and the 'peeled' outer layer had a higher organic C and N concentration than the inner core, but differences were not statistically significant. These authors suggested that stripping of this outer layer by raindrops can result in the production of material richer in chemical content than particles of the same size in the original soil. It is unclear whether the above results obtained by Ghadiri and Rose (1991) for a well aggregated (acidic) Vertisol from Australia (primary particle size = 61 per cent silt and clay; wet-sieved fraction $< 53\,\mu$m = 3 per cent, SOC = 3·5 per cent) are applicable to a well aggregated, highly weathered acidic Oxisol. To further examine this, parametric and non-parametric multiple difference tests were conducted to examine SOC variations for individual aggregate sizes between the original soil and splashed sediment from high and low EFD runs. If one-way analysis of variance (ANOVA) indicated a significant difference at $\alpha = 0{\cdot}05$, multiple comparisons were conducted using Fisher's least significant difference test. Data indicated that all wet-sieved aggregate fractions $> 105\,\mu$m from the original soil were either not significantly different from, or were significantly greater

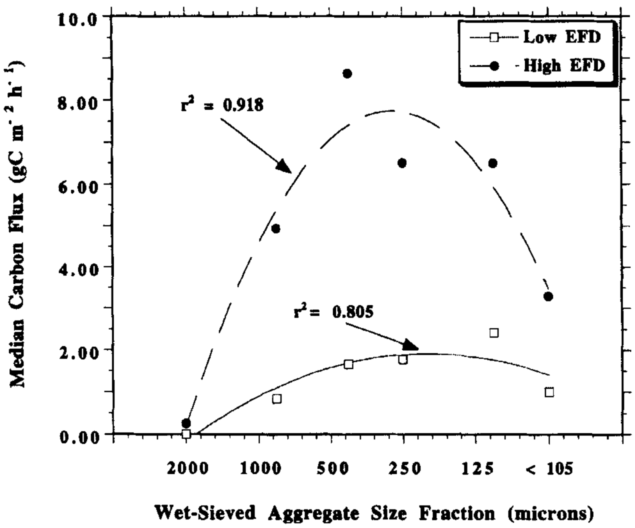

Figure 8. Carbon flux associated with various aggregate size fractions for two different energy flux densities (EFD). Each data point represents a median of 40 values. Note that 2000 implies a size range of 2000–4000 μm; 850, 850–1000 μm; 425, 425–850 μm; 250, 250–425 μm; 105, 105–250 μm

than, those produced by splash under high EFD conditions. This explains the differences noted in Figure 3 on a whole-soil basis. The only aggregate fraction exhibiting a statistically greater SOC concentration in the splashed sediment was the fraction < 105 μm (high EFD), and this was approximately 10 per cent greater than that for the original soil (cf. Table II). These results seem to indicate that stripping occurred from some of the larger aggregate fractions under high EFD conditions and thus produced aggregates < 105 μm which were higher in SOC than the original soil (i.e. $ER_{[SOC]}$ > 1·0; Figure 9). General trends indicated increased $ER_{[SOC]}$ values with decreasing aggregate size diameter, similar to the trends identified for a Vertisol by Ghadiri and Rose (1991) for splashed material after 50 min storm events (Figure 9; Table III). Additionally, splash data from Palis *et al.* (1990) for an acidic, sandy clay loam, Ultisol from Australia (SOC = 1·9 per cent) of lower aggregate stability than the soil used in this study or the one investigated by Ghadiri and Rose (1991), showed ER trends similar to those in Figure 9. After 35 min storm events with a simulator rainfall intensity of 100 mm h^{-1} they noted that only the < 38 μm aggregate fraction had a nitrogen ER value greater than 1·0. The only trend that was statistically significant in Figure 9 for the Oxisol data was that for the wet AMC–high EFD conditions ($r^2 = 0{\cdot}69$, $P < 0{\cdot}05$). Thus, raindrop stripping cannot be ruled out as a possible mechanism producing $ER_{[SOC]}$ values > 1·0 for Oxisol aggregates < 105 μm.

Values of splash $ER_{[SOC]}$ obtained in this study were significantly lower than the average literature value of approximately 2·0 for SOC or SOM (Table III). The ER values summarized in Table III, with the exception of the work by Ghadiri and Rose (1991), include combinations of interrill and rill erosion. However, general discussions, or even observations, concerning the relative importance of the erosion processes are lacking in these studies. High ER values for nutrients are commonly associated with selective removal of chemically enriched fines or selective deposition of coarse material, particularly by energy-limited interrill overland flow. Since splash and rill erosion processes are more energetic than interrill overland flow they are able to detach and transport a wider range of aggregates, and concomitantly nutrient ER values should be lower.

Variation in carbon mass enrichment ratios with AMC and EFD

Most of the discussion in the literature focuses on ER values based on concentration comparisons between the soil and sediment. However, few data are available which consider ER as a combination of concentration

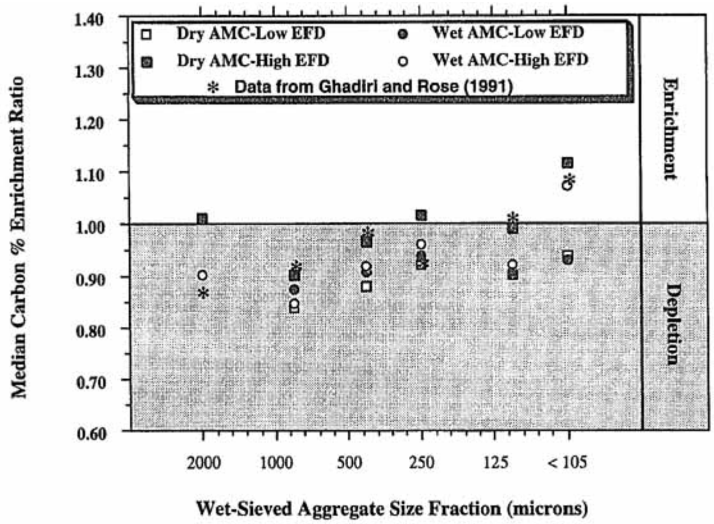

Figure 9. Carbon concentration enrichment ratio associated with various aggregate size fractions for different antecedent moisture content (AMC) and rainfall energy flux density (EFD). Each data point represents a median for a maximum of 20 observations. Note that 2000 implies a size range of 2000–4000 μm; 850, 850–1000 μm; 425, 425–850 μm; 250, 250–425 μm; 105, 105–250 μm

of a selected nutrient and mass flux of a given erosion agent. Thus, a mass-based carbon enrichment ratio (ER_{CMF}) was developed, Equation (2), for individual aggregate sizes. The variation in ER_{CMF} with aggregate size for various combinations of AMC and EFD (Figure 10) indicates preferential movement of C with splash aggregates of 250–2000 μm. This pattern was highlighted by fitting a third-order polynomial to all the data. This general pattern was similar to the splash ER curve (not shown), and indicates the importance of preferential splash of certain aggregate sizes in comparison to that for C concentration (Figure 9). Despite the aggregate fractions 250–425 μm and 425–850 μm having the lowest C concentrations (Table II), they preferentially transported C on a mass basis since these fractions were selectively removed in excess to their proportion in the original soil matrix. The 850–2000 μm fraction had the second highest C concentration in the original soil and this, combined with preferential splash, produced an $ER_{CMF} > 1{\cdot}0$. The aggregate fractions < 105 μm and > 2000 μm exhibited ER_{CMF} values significantly less than 1·0, and this was a function of their overall resistance to detachment (Figure 4). Thus, despite the initially dry and wet high EFD runs having $ER_{[SOC]}$ values greater than 1·0 this could not compensate for a splash ER value significantly less than 1·0, and the resulting ER_{CMF} value was $< 1{\cdot}0$. Though raindrop stripping may play a role in enriching the < 105 μm fraction in SOC, this fraction, owing to cohesion, particle shielding or particle filtration, was not preferentially transported on a mass basis.

Further research is required to characterize the ER_{CM} values for interrill overland flow, i.e. splash plus wash, and rill flow. Recent studies using the Wahiawa Oxisol have indicated that the geometric mean aggregate diameter of transported sediment was between 300 and 450 μm, compared to the *in situ* soil of 660–730 μm. Thus, the wash process was characterized by selective movement of fines, because overland flow had limited power to detach and transport the coarsest aggregates. Therefore, wash-dominated interrill flow will probably shift the carbon mass enrichment ratio illustrated in Figure 10 to the right. Under certain conditions interrill flow may not be dominated by wash processes, but rather transport to rills may be driven primarily by splash. This is contrary to the simple model of splash as a diffusive process. Laboratory work suggests that under steep, short, furrow side slopes (typical of agricultural landscapes), splash sediment flux may be equal to or greater than wash flux (Sutherland *et al.*, 1996) to rills. Thus, the modelling of soil carbon depletion by water erosion processes needs to consider the relative importance of splash and wash aggregate transport, and the overall balance between interrill and rill processes.

Table III. Literature summary of soil organic carbon (SOC) and soil organic matter (SOM) concentration enrichment ratios

Source*	Experimental conditions	Soil characteristics	Mean enrichment values	Additional comments
1	3% slope, 930 m^2, 1947–1950 Corn–oats–hay–hay rotation (Wisconsin)	Almena silt loam	$1·79 \pm 1·13^{\dagger}$ (52)‡	SOM, natural rainfall, rill and interrill processes presumed
1	11% slope, 372 m^2, 1947–1950 Corn–oats–hay–hay rotation (Wisconsin)	Fayette silt loam	$2·65 \pm 1·45^{\dagger}$ (23)	As above
1	20% slope, 223 m^2, 1947–1950 Grassland rotations (Wisconsin)	Fayette silt loam	$2·34 \pm 1·09^{\dagger}$ (70)	As above
1	9% slope, 372 m^2, 1947–1950 Five different rotations (Wisconsin)	Miami silt loam	$1·95 \pm 1·07^{\dagger}$ (32)	As above
2	Six watersheds, 2–5% slope, 0·81–1·46 ha, straight row planting and cultivation (Indiana)	Silt loam	1·24	As above
2	Six watersheds, 2–5% slope, 0·81–1·46 ha, contour planting and cultivation (Indiana)	Silt loam	1·38	As above
3	0·5% slope, 45 m^2, 3 yr data (India)	Sandy loam (63% Sa, 16% Cl)	4·56	As above
3	1·5% slope, 45 m^2, 3 yr data (India)	Sandy loam (62% Sa, 15% Cl)	4·10	As above
3	3·0% slope, 45 m^2, 3 yr data (India)	Loam (50% Sa, 21% Cl)	3·07	As above
4	Deposited sediments in 41 US impoundments	Seven soil orders	$1·30 \pm 0·77^{\S}$ (41) [range 0·24–6·30]	SOC, natural rainfall, rill and interrill processes presumed
5	0·2% slope, 15·6 ha, cotton (Mississippi)	Silty clay (1% Sa, 47% Cl), Inceptisol	$1·63 \pm 0·48^{\S}$ (5) [range 1·13–2·40]	SOM, natural rainfall, interrill processes dominant
6	4·0–8·0% slopes, plot 1·0 m (L) × 0·3 m (W), 60–120 mm h^{-1}, 1 h storms, wire mesh placed 4 cm above soil surface to reduce raindrop energy (Oklahoma and Texas)	Loamy sand (74% Sa, 8% Cl), Alfisol	$2·01 \pm 0·92^{\S}$	SOC, laboratory simulation, interrill overland flow
6	As above	Loam (34% Sa, 19% Cl), Mollisol	$2·46 \pm 0·68^{\S}$	As above
6	As above	Clay (10% Sa, 50% Cl), Vertisol	$2·44 \pm 1·23^{\S}$	As above
6	As above	Silt loam (33% Sa, 13% Cl), Mollisol	$1·97 \pm 0·57^{\S}$	As above
6	As above	Clay loam (21% Sa, 29% Cl), Mollisol	$1·48 \pm 0·23^{\S}$	As above
6	As above	Loam (28% Sa, 22% Cl), Mollisol	$1·65 \pm 0·46^{\S}$	As above
7	7% slope, 44 m^2, 63·5 mm h^{-1}, fallow (Minnesota)	Loam (48% Sa, 18% Cl), Mollisol	1·93	SOC, field rainfall simulation, rill and interrill processes presumed
7	As above	Loam aggregates < 63 μm	1·83	As above
7	As above	Loam aggregates 63–250 μm	1·69	As above
7	As above	Loam aggregates > 250 μm	1·48	As above
7	3% slope, 44 m^2, 76·2 mm h^{-1}, fallow (Mississippi)	Silt (10% Sa, 15% Cl), Alfisol	2·56	As above
7	6% slope, 44 m^2, 63·5 mm h^{-1}, conventional tillage (Indiana)	Silt (24% Sa, 17% Cl), Alfisol	1·65	As above
7	As above but with chisel ploughing (Indiana)	Silt (24% Sa, 17% Cl), Alfisol	1·41	As above
7	As above but with no-till management (Indiana)	Silt (24% Sa, 17% Cl), Alfisol	2·21	As above

Table III (Continued). Literature summary of (SOC) and (SOM) concentration enrichment ratios

Source*	Experimental conditions	Soil characteristics	Mean enrichment values	Additional comments
8	4·5% slope, 300 m^2, 2057 storms, 39 plots (Zimbabwe)	Three Alfisols and one Entisol	$2·39 \pm 1·40^{§}$ [range 0·78–9·25]	SOC, natural rainfall, rill and interrill processes presumed
9	$\approx$ 0% slope, 6 m^2, 100 mm h^{-1}, 50 min duration	Clay (29% Sa, 55% Cl) Vertisol – < 106 μm fraction	1·08	SOC, laboratory rainfall simulation, splash
9	As above	106–250 μm fraction	1·03	As above
9	As above	250–500 μm fraction	0·93	As above
9	As above	500–1000 μm fraction	0·97	As above
9	As above	1000–2000 μm fraction	0·89	As above
9	As above	> 2000 μm fraction	0·86	As above

*Reference sources: 1 = Massey and Jackson (1952); 2 = Stoltenberg and White (1953); 3 = Goel *et al.* (1968); 4 = Avnimelech and McHenry (1984); 5 = McDowell *et al.* (1984); 6 = Sharpley (1985); 7 = Young *et al.* (1986); 8 = Stocking (1988); 9 = Ghadiri and Rose (1991)

†95% confidence band on the mean

‡Number of observations

§± One standard deviation from the mean

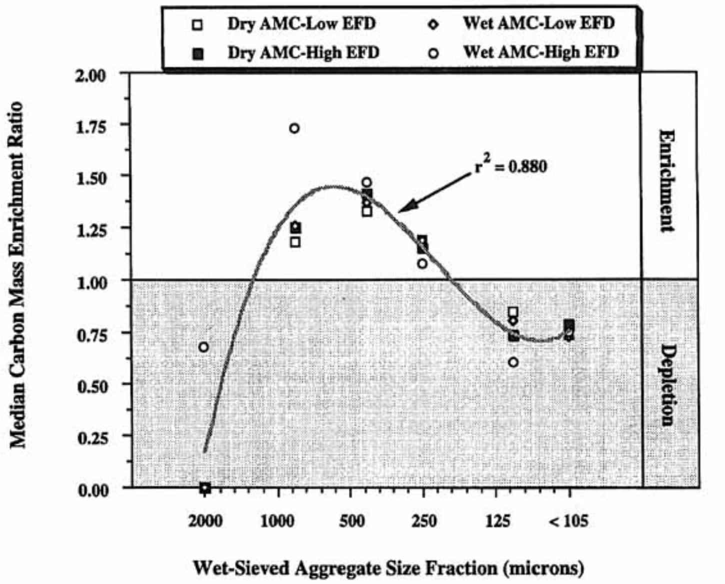

Figure 10. Carbon mass enrichment ratio associated with various aggregate size fractions for different antecedent moisture contents (AMC) and rainfall energy flux densities (EFD). Each data point represents a median for a maximum of 20 observations. Note that 2000 implies a size range of 2000–4000 μm; 850, 850–1000 μm; 425, 425–850 μm; 250, 250–425 μm; 105, 105–250 μm

CONCLUSIONS

In this rainfall simulation study an Oxisol was used to document the influence of different moisture controls and raindrop energies on splash flux, soil organic carbon flux, soil organic carbon concentration and mass enrichment ratios. The original soil exhibited significant differences in C concentration in the wet-sieved aggregate size fractions, with the lowest mean value for the 250–425 μm fraction (16·9 gC kg soil^{-1}), and the highest value for the < 105 μm fraction (20·1 gC kg soil^{-1}). The concentration difference between fractions is similar to that reported for other highly weathered acidic Oxisols from Australia and Brazil.

Splash flux increased significantly with increased rainfall energy for both dry and wet initial moisture conditions. These data are in keeping with those published for temperate soils. Additionally, total carbon flux increased with increased EFD regardless of initial moisture content. No comparative data are presently available from the literature. Aggregate size was noted to have a significant influence on C splash resistance to detachment, with the 2000–4000 μm fraction requiring about 16 times the energy to remove 1 gC than for the 425–850 μm fraction.

Temporal patterns of cumulative C splash flux for various combinations of AMC and EFD mirrored those for splash. During wet runs, peak flux occurred during the 0–15 min period when there was maximum availability of aggregates of all sizes, and limited sealing by raindrop compaction. Development of a uniform water layer did not occur since the splash cup design prevented this, but observations indicated that water filling to an unknown depth did occur in transient drop impact craters. Thus, this may have resulted in decreased splash with time if the crater water layer was deep enough to cushion the drop impacts. During dry runs splash increased with time as aggregate breakdown occurred, probably as a result of slaking. With increased aggregate availability and decreased soil strength, due to increased moisture content, splash and C flux increased. Peak flux occurred during 30–45 min for the high EFD experiments, and during the final time increment for the low EFD runs. Overall, the dry AMC–high EFD runs produced the greatest splash and the greatest C mass output.

On an individual aggregate size basis differences in C flux were mainly controlled by rainfall energy conditions. Comparisons of C concentrations for individually splashed aggregate fractions with the original soil matrix indicated that only the $< 105\,\mu m$ fraction exhibited enrichment during the high EFD runs. On the other hand, C concentration enrichment ratios for the other fractions were generally $\leq 1{\cdot}0$. The enrichment in the $< 105\,\mu m$ fraction may be explained by raindrop stripping of an outer, chemically enriched aggregate layer and production of material enriched in comparison to similar sized aggregates in the original soil (cf. Ghadiri and Rose, 1991). Though stripping may have occurred it did not produce a C mass enrichment ratio $> 1{\cdot}0$ for the finest fraction. Only fractions between 250 and $2000\,\mu m$ had C mass enrichment ratios $> 1{\cdot}0$. These results indicate that the simple computation of nutrient concentration enrichment ratios may be misleading, since it is generally the mass flux of a given nutrient that is environmentally critical. Thus, development of nutrient mass enrichment ratios is preferred, and needs to be considered for future incorporation in chemical transport models.

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